

# HIGH-ENERGY GAMMA AND NEUTRINO ASTRONOMY<sup>a</sup>

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An overview is given of high-energy gamma-ray and neutrino astronomy, emphasizing the links between the two fields. With several new large detectors just becoming operational, the TeV gamma-ray and neutrino sky will soon be surveyed with unprecedented sensitivity.

## 1 Introduction

These are exciting times for high-energy gamma ray and neutrino astronomy. During the last couple of years several sources of TeV gamma rays have finally been convincingly detected, after many years of marginal and sometimes erroneous claims of detection at higher energies in air shower arrays.

This healthy development of the field is due to the operation of several new large experimental facilities, in particular the CASA, HEGRA and Whipple experiments (for a summary of these experiments, see Ref. <sup>1</sup>).

In neutrino astronomy, the first sources beyond the Sun (and the transient SN 1987A) remain to be discovered. There are great expectations that this will happen soon, as new large neutrino telescopes are just about to become operational.

There are several areas of intersection between gamma ray and neutrino astronomy. By both probes one gets a view of violent astrophysical processes, and in contrast to charged cosmic rays the direction to the source is preserved. Most of the processes that give rise to high-energy neutrinos should also generate gamma rays, and vice versa. By studying both types of emission valuable information about the production mechanisms of these energetic particles can be obtained. Due to the difference in absorption (TeV gamma rays are absorbed on IR intergalactic photons, whereas neutrinos are unaffected), useful information on the intergalactic radiation field may be obtained if far-away sources are observed.

Besides the more “mundane” local processes creating gamma rays and neutrinos, such as cosmic ray collisions with interstellar gas and dust, or with the Earth’s atmosphere, there are some very intriguing sources like the central parts of Active Galactic Nuclei (AGN) and some more exotic possibilities like

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radiation from nonbaryonic dark matter annihilations and from topological defects. While a discovery of the latter class of course would be quite remarkable, also non-discovery is useful to establish limits on the underlying particle physics theories.

## 2 High-Energy Gamma Rays

Traditionally, gamma ray astronomy has been divided into several subfields based on the energy range studied, from the MeV region all the way up to YeV ( $10^{21}$  eV). This is due to the fact that completely different experimental techniques are used, and also different physical processes are involved in the sources.

In fact, due to the overwhelming background of low-energy gamma rays produced in the atmosphere by the intense cosmic ray flux, it is necessary to use space detectors to detect gammas of energy below roughly 50 GeV. Above that energy, ground-based air Cherenkov telescopes of much larger area may be employed. With instruments on board the Compton-GRO satellite, notably the EGRET detector<sup>2</sup>, data is now available up to 20 GeV. The EGRET catalog comprises a large number of supernova remnants and AGNs, but also many sources of unknown origin. An interesting new result is that the diffuse  $\gamma$  ray flux from the galactic center recently detected by EGRET seems to show some evidence of an excess at high energy which is not easily explained in conventional models<sup>3</sup>.

At present, there is an annoying gap in the energy range between around 20 and 250 GeV, above which energy the most advanced ground-based air Cherenkov telescopes become functional. The principle of these is to detect in optical mirrors the Cherenkov radiation caused by air showers initiated by the primary particles. Above around 10 TeV, some particles of the air showers penetrate all the way down to the surface (at least at mountain altitudes) and can be detected directly. In air shower arrays these cascades are sampled sparsely but over large areas.

The energy gap will most probably be filled from both sides the next few years as, e.g., both new space detectors (like GLAST<sup>4</sup>) and large solar power plant mirror arrays<sup>5</sup> are planned to be deployed.

The problem of establishing a signal from a gamma ray point source is highly nontrivial, since the cosmic ray flux, roughly  $10^{-7}$  cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> at 10 TeV, is much higher than any expected gamma ray flux. The low signal to noise was probably the reason for some seemingly erroneous claims of detection of galactic point sources in the 1980's, something that was rectified by the standard-setting CASA experiment<sup>6</sup>.

The last two or three years, remarkable improvements in the imaging qualities and hadron rejection of air Cherenkov telescopes has finally resulted in solid detection of the first few TeV gamma ray point sources. The first one to be detected, with remarkably high statistics by the Whipple group<sup>7</sup>, was the Crab nebula. (It was confirmed by several other groups like ASGAT, Themistocle, CANGAROO and TIBET.) The pulsar-driven Crab supernova remnant is such a solid TeV gamma ray source that it has become something of a standard candle for high-energy gamma ray astronomy today.

The jets of AGN had also been hypothesized as being possible TeV gamma ray sources, since there is a Lorentz boost for jets viewed head-on. A complication here is that for extragalactic sources, the optical depth of gamma rays may become non-negligible. A gamma ray traveling through the intergalactic medium will interact with a high cross section with photons of energy corresponding to an invariant mass just above the  $e^+e^-$  cross section. For a TeV photon, this means a sensitivity to IR photons at  $\sim 2\mu\text{m}$ . (Note that the cosmic microwave background cuts off PeV  $\gamma$  radiation at a fraction of a Mpc.)

Recently, a detailed analysis<sup>8,9</sup> using the most recent determinations of the optical and IR intergalactic background, has shown that TeV sources more distant than  $z \sim 0.1$  should hardly be seen due to absorption. Recent observations seem to verify this general picture.

The first observation of TeV gammas from an AGN was made by the Whipple collaboration<sup>10</sup>, who detected a signal from the blazar Mkn 421 at the  $6\sigma$  confidence level. Recently, the HEGRA collaboration independently confirmed this source using two of their instruments<sup>11</sup>. Another blazar, Mkn 501, which is too weak a GeV source to be detected by EGRET, has recently been seen in TeV  $\gamma$ s by both Whipple and HEGRA<sup>12</sup>.

A most remarkable, rapid outburst of TeV  $\gamma$ s from Mkn 421 was detected by the Whipple group on May 7th, 1996<sup>13</sup>. With a doubling time of about one hour, the flux increased above the quiescent value by a factor of more than 50, making this source even brighter than the Crab in TeV  $\gamma$  radiation. In a second outburst about a week later, the flux increased by a factor of almost 25 in approximately 30 minutes. This type of violent variability on very short time scales is bound to severely strain current models, although interesting attempts have appeared<sup>14</sup>.

At this Conference, new results were presented from the HEGRA collaboration<sup>15</sup>, indicating that there may be a handful of additional TeV sources (in fact, even above 30 TeV) among the nearby ( $z \lesssim 0.06$ ) EGRET sources. If this is confirmed, it should have interesting consequences for the intergalactic IR and optical background. This could give useful information on the mechanisms for early galaxy formation<sup>9</sup>.

The origin of the high-energy radiation from AGNs is still unclear. It seems probable that shock acceleration is involved near the black hole or, for the blazar class, in the jet, but how particles are transferred to the outer regions as well as how they interact is still mysterious. In fact, it is not known whether leptons or hadrons are mainly responsible for energy transport near the accretion region. It is conceivable that electrons, interacting with ambient magnetic fields, create synchrotron radiation which in turn may be inverse-Compton scattered to high energies. These are the so-called SSC (synchrotron self-Compton) models<sup>16</sup>, which work very successfully for a supernova remnant like the Crab. In another class of models<sup>17</sup>, mainly hadrons (protons) are accelerated, which interact with the dense photon gas in the AGN central region or in a jet. In  $p\gamma \rightarrow \pi + X$  reactions, high-energy neutrinos, electrons, positrons and gamma rays are created in the decay of pions. All particles except the neutrinos induce electromagnetic cascades which terminate at low energy. In particular, the X-ray flux may be used to put an upper bound on the neutrino rates in this class of models<sup>18,19</sup>. Although estimates are uncertain, it seems that the integrated rate from all AGNs may give a “diffuse” source of very high energy neutrinos which could be detectable in the new generation of neutrino telescopes like AMANDA.

It appears that if the recent detection of  $\gamma$ s of more than 30 TeV from several blazars<sup>15</sup> is confirmed, it may lend credibility to the hadronic model<sup>20</sup>. A solid answer must, however, await a detailed analysis of time-correlated multi-waveband data and/or the findings from neutrino telescopes.

### 3 High-Energy Neutrinos

Neutrino astronomy was born with the first detection of solar neutrinos (too few to fit standard solar models) by R. Davis et al. in the 1960s, with the proof two decades later by the Kamiokande collaboration that the neutrino events really point back to the Sun. The solar neutrino problem is of course still one of the most intriguing indications we have for physics outside the Standard Model of particle physics<sup>21</sup>. The remarkable detection of neutrinos from SN1987A in the Kamiokande and IMB detectors (originally constructed to search for proton decays) has established neutrino astronomy as a useful branch of astrophysics. In addition, the observed neutrino rates from the SN1987A event has helped particle physicists to put limits on neutrino properties as well as on various hypothetical, weakly interacting particles. Indeed, neutrino astrophysics is one of the areas where the connections between astrophysics and particle physics are perhaps the strongest.

The first neutrino telescopes typically had effective areas of the order of

one to a few hundred  $\text{m}^2$ . They have been followed by a new generation (MACRO, Super-Kamiokande) which approaches  $10^3 \text{ m}^2$ . Super-Kamiokande, for instance, is an extremely well-equipped and sensitive laboratory for all types of neutrino physics of energy from a few MeV upwards<sup>22</sup>. MACRO has recently published<sup>23</sup> its first measurement of the atmospheric neutrino flux above 1 GeV.

However, for TeV neutrino energies and above, all estimates indicate that the effective areas must be much larger to give a fair chance of detection<sup>24</sup>. Therefore, a new generation of very large telescopes has been developed, which sacrifice sensitivity of MeV neutrinos for large area ( $10^4$  to  $10^5 \text{ m}^2$  at present - the aim is for  $1 \text{ km}^2$  within a few years) for multi-GeV neutrinos. (Typical thresholds are some tens of GeV.) A pioneer of this type was the deep ocean DUMAND experiment<sup>25</sup> outside Hawaii, which now seems to be discontinued at the prototype stage due to various technical problems related to the very demanding ocean environment. However, even with a small prototype, they were able to put some limits on cascades initiated by AGN neutrinos<sup>26</sup>, showing the promise of this type of technique. In Europe, the ocean detector concept is being further investigated in the Mediterranean by the NESTOR<sup>27</sup> and ANTARES<sup>28</sup> collaborations, with a large-scale detector still being a couple of years ahead.

The Lake Baikal experiment<sup>29</sup> has become the first of the natural-water detectors to successfully detect atmospheric neutrinos, although only a few events so far in its 96-fold OM (optical module) array. The array is successively being expanded to 200 OMs, with 3/4 of that expected by the spring of 1997. It has the advantage over ocean detectors of being in fresh water, thus avoiding the high radioactive background from  $^{40}\text{K}$  present in salt water. Also, the ice cover during winter months helps the logistics of the deployment substantially. However, bioluminescence is present and sedimentation necessitates regular cleaning of the optical modules. In addition, the relatively shallow depth (1300 m) means that a large background of downward atmospheric muons has to be fought. It is an impressive achievement of the Baikal group to have obtained the up/down rejection factor needed to detect upward-going muons.

In the deep under-ice US-German-Swedish detector AMANDA at the South Pole, none of these problems is present (although the maximum useable depth of around 2500 m still gives substantial downward-going muon flux). On the other hand, it was not clear before last year that the ice quality was good enough to deploy a large detector. In particular, a prototype deployed in 1994-95 at 800 to 1000 m depth showed severe degradation of timing resolution due to scattering on residual air bubbles at that depth. However, ice inbetween air bubbles was found to be remarkably clean, with absorption lengths in the

near-UV being more than ten times longer than ever measured in laboratory ice<sup>30</sup>.

In the 1995-96 season, 4 strings of 20 OMs each (20 m spacing between OMs) were deployed to 2000 m depth, and the scattering on bubbles was found to be absent (or at least two orders of magnitude smaller than at 800 m), permitting the first muons to be tracked<sup>31</sup>. In the soon finished, highly successful 1996-97 season, 6 additional strings have been deployed. Thanks to improvements in signal transmission, thinner twisted quad cables could be used permitting 36 OMs per string, with now 10 m separation between OMs. The average distance between nearest-neighbor strings in the 10-string detector is around 30 m. Of the 216 new OMs, only half a dozen have failed, giving the AMANDA collaboration the hope of soon having at its disposal a detector of around  $10^4$  m<sup>2</sup> for upward-going single muons, and much larger for cascades initiated, e.g., by electron neutrinos.

### 3.1 Sources of High-Energy Neutrinos

In a large detector, like the present AMANDA neutrino telescope, there will be a real chance to detect neutrinos from AGNs, if the models involving acceleration of hadrons are correct. Besides the “diffuse” integrated contribution from all AGNs, which could amount to several hundred events per km<sup>2</sup> per year<sup>24</sup>, the blazars (i.e. AGNs with jets viewed nearly head-on) from the EGRET catalog will be promising objects to study. The fact that the TeV gamma ray sources seen by air Cherenkov telescope are all relatively nearby, whereas many stronger such EGRET sources are not seen in TeV gammas, has as its most natural explanation the intergalactic absorption of gamma rays. Thus there could be a large number of very intense neutrino sources awaiting discovery.

The fact that whenever hadrons are accelerated, both gamma rays and neutrinos will be produced through pion decay, means that models, e.g., for gamma ray bursts (GRBs), where hadronic fireballs are excited inevitably predict also neutrino radiation<sup>32,33</sup>. In the AMANDA detector, a trigger has been set up which can correlate an excess of neutrino events with satellite detection of a GRB. (A supernova trigger is also implemented.) As has been pointed out<sup>33,34</sup>, if an extragalactic source of neutrinos is found, there are many interesting tests of neutrino properties (mass, mixings, magnetic moments etc) that can be made, which would supersede terrestrial tests and constraints from SN1987A by orders of magnitude.

If very-high energy (PeV) neutrinos from AGNs are present, a whole range of other exotic particle physics processes could be investigated as well (such as leptoquarks, multi-W processes etc<sup>35</sup>). An interesting process in addition is

the resonant  $\bar{\nu}_e + e^- \rightarrow W^-$  at around 6 PeV, which could give spectacular, background-free cascades in Cherenkov detectors.<sup>36,35</sup> In fact, for such high energies, the way to get a large effective detector volume may be to use the coherent radio wave radiation from the shower in the ice.<sup>37</sup> Prototype radio detectors have been deployed piggy-back on AMANDA strings this year.

### 3.2 Indirect Detection of Supersymmetric Dark Matter in Neutrino Telescopes

Supersymmetric neutralinos with masses in the GeV–TeV range are among the leading non-baryonic candidates for the dark matter in our galactic halo. One of the most promising methods for the discovery of neutralinos in the halo is via observation of energetic neutrinos from their annihilation in the Sun and/or the Earth<sup>38,39,40</sup>. (In some regions of parameter space, also detection in gamma rays in air Cherenkov telescopes through the unique signature of a line of narrow width, could be feasible<sup>41</sup>.) Neutralinos do not annihilate into neutrinos directly, but energetic neutrinos may be produced via hadronization and/or decay of the direct annihilation products. These energetic neutrinos may be discovered by terrestrial neutrino detectors.

The prediction of muon rates is in principle straight-forward but technically quite involved: one has to compute neutralino capture rates in the Sun and the Earth, fragmentation functions in basic annihilation processes, propagation through the solar or terrestrial medium, charged current cross sections and muon propagation in the rock, ice or water surrounding the detector.

The neutralinos  $\tilde{\chi}_i^0$  are linear combinations of the neutral gauginos  $\tilde{B}$ ,  $\tilde{W}_3$  and of the neutral higgsinos  $\tilde{H}_1^0$ ,  $\tilde{H}_2^0$ , the lightest of which, called  $\chi$ , is then the candidate for the particle making up (at least some of) the dark matter in the universe.

With Monte Carlo simulations one can consider the whole chain of processes from the annihilation products in the core of the Sun or the Earth to detectable muons at the surface of the Earth.

Unfortunately, no details about supersymmetry breaking are known at present, which means that a lot of parameters are undetermined. The usual strategy<sup>39,40,38</sup> is then to scan the parameter space of the minimal supersymmetric extension to the Standard Model.

The best present limits<sup>42</sup> for indirect searches come from the Baksan detector. The limits are  $\Phi_\mu^{Earth} < 2.1 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$  and  $\Phi_\mu^{Sun} < 3.5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$  at 90% confidence level and integrated over a half-angle aperture of  $30^\circ$  with a muon energy threshold of 1 GeV. This has already allowed some models to be excluded<sup>40</sup>. A neutrino telescope of an area around  $1 \text{ km}^2$ , which is a size currently being discussed for a near-future neutrino telescope, would

improve these limits by two or three orders of magnitude and would have a large discovery potential for supersymmetric dark matter.

Indirect dark matter searches and LEP2 probe complementary regions of the supersymmetric parameter space. Moreover, direct detection<sup>38</sup> is reaching a sensitivity that allows some models to be excluded<sup>43</sup>, with somewhat different characteristics than those probed by the other methods. This illustrates a nice complementarity between direct detection, indirect detection and accelerator methods to bound or confirm the minimal supersymmetric standard model.

### *3.3 Establishing a Neutrino Signal from a Point Source*

For neutralino detection, as well as for other physics objectives of neutrino telescopes, a problem will always be the irreducible background coming from atmospheric neutrinos. However, a typical signal will appear as a peak in the angular distribution; usually the energy distribution is different as well. The question of how the discovery potential depends on the angular and energy resolution has recently been investigated<sup>44</sup>.

Due to the finite muon production angle, one would like to accept muons from a large enough solid angle around the point source to assure all the signal events are accepted. For example, the rms angle between the neutrino direction and the direction of the induced muon is  $\sim 20^\circ / \sqrt{E_\nu / 10 \text{ GeV}}$ . Furthermore, the muon typically carries half the neutrino energy, so the angular radius of the acceptance cone should be  $\sim 14^\circ / \sqrt{E_\mu / 10 \text{ GeV}}$ . The problem is of course that the a priori energy of signal neutrino events is unknown, so one has to optimize angular and energy acceptance according to varying hypotheses for the neutrino source.

A general covariance-matrix formalism has been set up<sup>44</sup> and applied to the specific example of neutralino annihilation in the Sun and Earth, for detectors with various values of angular and energy resolution. Comparing, e.g., the improvement by using a 3-parameter fit for the signal to the simple case of using just one bin up to a certain angle  $\theta_{\text{max}}$  one finds that there could be an improvement of up to a factor of 2 at high masses. Although this application was for neutralino annihilation, the formalism<sup>44</sup> is general enough to be applicable for a generic point source. As large neutrino experiments now come on-line, we can expect successive improvements in their discovery potential.

### **Conclusions and Acknowledgments**

With new windows to the universe, historically it has always been the case that unexpected discoveries have appeared. I have tried to summarize the status and expectations for high-energy gamma ray and neutrino astronomy.



Maybe the outcome will be different than predicted here, but it certainly will be interesting.

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